Feb. 26, 1957 H. R. WARREN 2,783,349

HIGH-FREQUENCY HEATING APPLICATORS

Filed March 26, 1954 2 Sheets-Sheet 1

Fig. 1

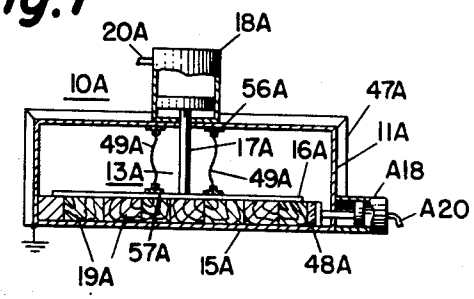


Fig. 3

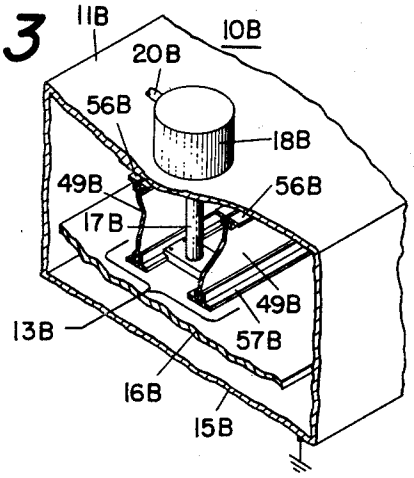


Fig. 2

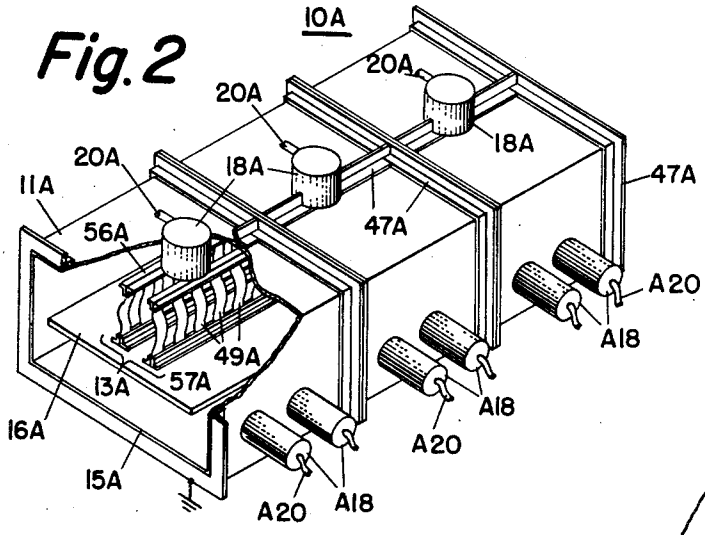


Fig. 5

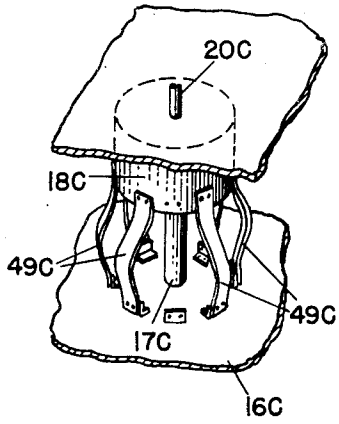
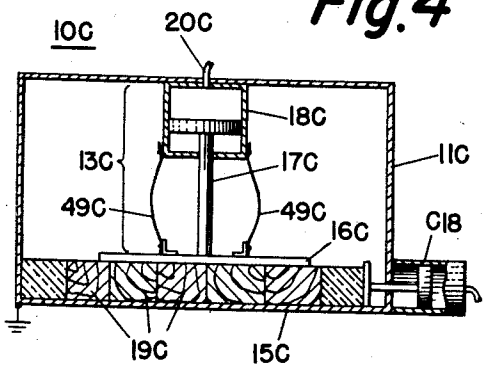


Fig. 4



Feb. 26, 1957 H. R. WARREN 2,783,349

HIGH-FREQUENCY HEATING APPLICATORS

Filed March 26, 1954 2 Sheets-Sheet 2

Fig. 6

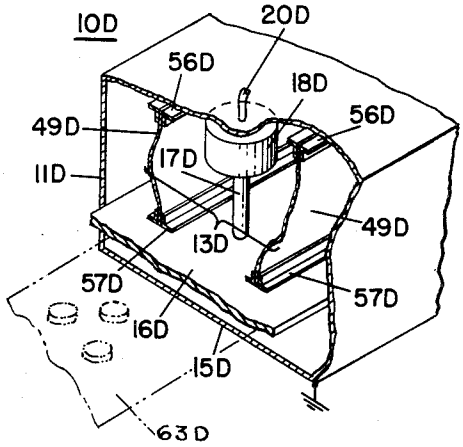


Fig. 7

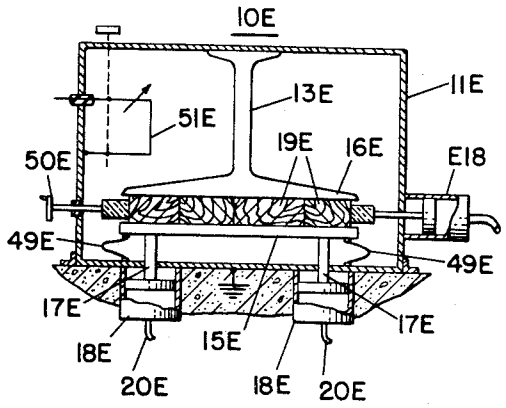


Fig. 8

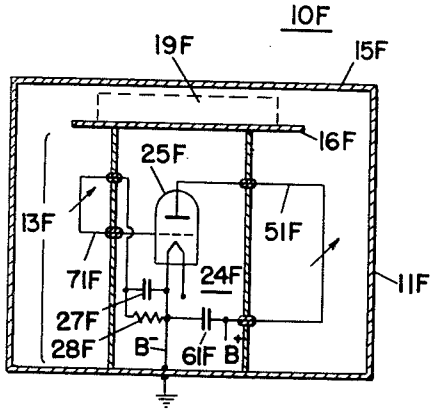
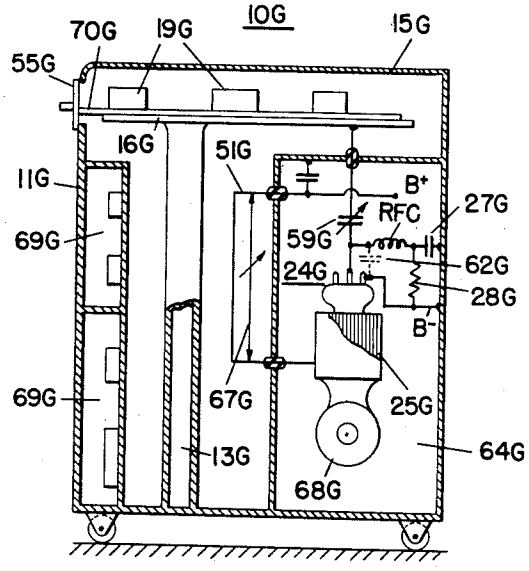


Fig. 9



United States Patent Office 2,783,349 Patented Feb. 26, 1957

2,783,349

HIGH-FREQUENCY HEATING APPLICATORS

Henry R. Warren, Columbus, Ind., assignor to National Cylinder Gas Company, Chicago, Ill., a corporation of Delaware

Application March 26, 1954, Serial No. 419,070

21 Claims. (Cl. 219—10.55)

This invention relates to high-frequency heating and particularly to resonant applicators especially suited for rapid dielectric heating of large area loads, such as foam-rubber mattresses, wallboard panels, groups of sand cores or plastic preforms, and the like, and other similar applications of high-frequency heating, wherein it frequently is required, or at least desirable, that the "hot" heating electrode be of large area, i. e., in the order of several feet in one or both face dimensions.

This application, a continuation-in-part of my application Serial No. 138,628, filed January 14, 1950, and now abandoned in favor of my continuation-in-part application Serial No. 419,633, filed March 26, 1954, has claims directed to subject matter divided from my parent application Serial No. 138,628. My aforesaid applications contain a more detailed discussion, included herein by this reference, of the structural and operating characteristics of resonant applicators of the kind to which the present invention is particularly directed.

In general, such applicators comprise relatively large electrode structures electrically interconnected through conductive structure which at least in part has substantial inductance cooperative with capacity-means including the capacitance between said electrode structures to form a resonant circuit device, and a power transfer coupling loop disposed in position to be traversed by a high-frequency magnetic field encircling a part of said interconnecting conductive structure. More particularly, in the preferred form of such applicators, the interconnecting structure includes low-resistance, low-reactance conductive walls of a shielding enclosure which completes the resonant circuit of said device and serves to confine said magnetic field and also the electric field produced between said electrode structures, at least one of the electrode structures being electrically interconnected with wall structure of the enclosure through a leg or fin-like element which projects into the enclosure and in which a substantial part of the inductance of the resonant applicator is concentrated, and the said coupling loop being arranged to be traversed by the magnetic field encircling the inwardly projecting leg or fin-like element. Such loop may serve to provide for excitation of the applicator by, preferably but not limited to, a self-excited oscillator having the loop in its anode circuit.

In accordance with one important aspect of the present invention, the inwardly projecting leg or fin-like element is made in the form of a hollow structure, with numerous resulting advantages as will be pointed out hereinafter. Such hollow inductance structure may be of rectangular, round, octagonal or other suitable cross-sectional outline, and may be either similar to or unlike the outline of the associated electrode structure, depending upon the particular heating application encountered and structural requirements of the applicator as a whole. Moreover, the leg or fin-like element may be dimensioned and shaped so as to obtain an applicator inductance which has high Q. In addition, by proper dimensioning and shaping of the fin-like inductance structure, and by proper

location thereof either symmetrically or unsymmetrically with respect to the associated electrode structure, voltage gradients in various directions along large heating electrodes may be minimized or controlled without the necessity for resorting to "stubbing" with its attendant disadvantages and complications. When the spacing between the electrode structures is to be variable to accommodate therebetween loads of different heights, the hollow inductance structure may be extensible and to such end it may comprise, at least in part, metal straps or webs or other suitable flexible conductive elements.

The hollow inductance structure, in accordance with another important feature of the present invention, may be made so as to provide a shielded compartment in which associated mechanical or electrical apparatus, such as electrode raising devices, oscillator circuit components, and the like, may be disposed in substantial isolation from the intense high-frequency magnetic and electric fields of the applicator.

The invention further resides in high-frequency heating applicators having features of construction and arrangement hereinafter described and claimed.

For a more detailed understanding of the invention and for illustration of various embodiments thereof, reference is made to the accompanying drawings in which:

Fig. 1 is a sectional view of a press applicator;

Fig. 2 is a perspective view, partly broken away, of the applicator shown in Fig. 1;

Fig. 3 is a perspective view, with parts broken away, of a modification of the applicator shown in Figs. 1, 2;

Fig. 4 is a sectional view of a further modification;

Fig. 5 is a perspective view, with parts broken away or omitted, of the applicator of Fig. 4;

Fig. 6 is a perspective view, with parts broken away or omitted, of a modification of the applicator of Figs. 4, 5;

Fig. 7 is a sectional view of an inverted press-applicator; and

Figs. 8 and 9 are sectional views of other resonant applicators of non-press type.

The dielectric-heating press-applicator **10A** shown in Figs. 1 and 2 is particularly suited for production of laminated plywood sheets of substantial area (for example, 4 feet by 8 feet sheets), for production of large panels by edge-bonding of wooden strips, and for like purposes requiring large heating electrodes and dissipation of many kilowatts of radio-frequency power in the dielectric load. The press frame is in the form of an elongated metal tunnel **11A** of substantially rectangular cross-section.

A plurality of pressure-applying devices, specifically cylinders **18A** supplied from pressure lines **20A**, are spaced lengthwise of the tunnel **11A** with their plungers or rams **17A** attached, without interposition of insulation, to correspondingly spaced regions lengthwise of the elongated, movable platen **16A** which serves as the "hot" electrode of the applicator. In this modification, as well as in others herein described, the bottom of the tunnel may itself serve as the lower or "cold" heating electrode **15A**. Alternatively, the "cold" electrode may be an auxiliary conductive member, movable or stationary, conductively connected or otherwise coupled to the tunnel wall structure.

For applying lateral pressure to the heating load, as in edge-bonding of wooden strips **19A**, the applicator frame may be provided with a second series of pressure-applying devices, exemplified by cylinders A18 supplied from pressure-lines A20, having plungers or rams for applying lateral pressure to the work strips **19A** either directly or through an interposed filler block **48A**.

The tunnel walls may be relatively thin sheet metal reinforced, as suggested by frame members **47A**, to pro-

vide the strength and rigidity necessary to resist deformation by the pressure. The dimensions and disposition of the reinforcing members may vary widely to suit the pressure-resisting requirements of different installations. In edge-bonding, the pressure applied horizontally is quite substantial: the pressure applied vertically is relatively light but sufficient to prevent buckling by the applied side pressure.

The row of plungers 17A is within a hollow inductance structure or fin 13A defined by the two rows of straps 49A extending lengthwise of electrode 16A on opposite sides of the plungers with each strap connected from electrode 16A to the top wall of the tunnel. More specifically, the upper ends of the straps may be connected to the bars 56A attached to the top walls of housing 11A and the lower ends of the straps may be connected to bars 57A attached to the upper face of electrode 16A.

In the arrangement of Figs. 1 and 2, all, or practically all, of the inductance of the reentrant resonant applicator is concentrated in the hollow vertical fin structure 13A afforded by the parallel, elongated rows of straps 49A, and the applicator is resonant at a frequency predominantly determined by the inductance of the fin structure and the capacitance between the heating electrodes 15A, 16A. These straps 49A are preferably of relatively springy metal of high electrical conductivity, such as beryllium-copper or some other springy metal coated with copper or other metal of high conductivity.

The high-frequency magnetic field of the applicator encircles the reentrantly extending hollow fin 13A and is practically entirely confined in the tunnel space above electrode 16A. The high-frequency electric field of the applicator is practically entirely concentrated between the electrodes 15A, 16A and any supplemental capacity areas that may be associated therewith as in certain of the embodiments disclosed in my aforesaid copending application. The space within the hollow fin (i. e., between the rows of straps 49A) is effectively isolated from these high-frequency fields by the rows of straps 49A and the shielding of the inwardly extending end of the fin or inductance structure 13A by the electrode 16A. The spaced rows of straps define a substantially field-free or isolated compartment for the plungers 17A. Thus, the electrode-actuating members or plungers (17A) need not include or be comprised of insulating material, nor do they need be of metal having high electrical conductivity and in good electrical contact with the housing wall.

The high-frequency resistance of the hollow inductor 13A and of the "hot" electrode 16A is very low. The resistance of the remainder of the current path afforded by the extensive area of the wall structure of the tunnel is also very low so that, as in all applicators herein described, the Q is very high despite the high ratio of capacitance to inductance.

Because of their high-frequency, the circulating currents, which may be over a thousand amperes, are practically confined to the inner surfaces of the applicator housing and consequently all external surfaces including the cylinders 18A, A18 and the pressure-lines 20A are at ground potential. The applicator housing serves as a radio-frequency shield for the internal components which are at very high radio-frequency potential. Therefore the radiation losses are low, which minimizes radio interference and further contributes to high Q of the tunnel applicator.

Another and very important advantage of this type of applicator is its unique suitability for dielectric heating of load materials having very low power-factor including foam rubber, extruded rubber hose and gaskets, while also being suitable for heating high power-factor materials, such as wood.

The applicator 10B of Fig. 3 is of construction similar to that of Figs. 1, 2 except that the two rows of straps 49A are replaced by two wide sheets 49B on opposite sides of the row of plungers 17B with each sheet connected from

electrode 16B to the top wall of housing 11B so to define an elongated hollow fin inductance 13B within whose field-free space the electrode-actuating plungers 17B, or equivalent, are disposed. The sheets 49B are preferably of relatively springy metal of high electrical conductivity, such as beryllium-copper or some other springy metal coated with copper or other metal of high conductivity. This modification need not be further described as the description of Figs. 1, 2 is similarly applicable thereto.

In the modified form of press applicator 10C shown in Fig. 4, the construction is similar to that shown in Figs. 1 to 3 except that the vertical cylinders 18C are within the applicator housing and serve as a substantial part of the inductance of the resonant applicator. Preferably however, each of the plungers 17C is effectively shunted, as shown in Fig. 5, by a circular array of conductive straps 49C connected at their lower ends to the upper face of electrode 16C. The upper ends of straps 49C engage and are preferably fastened to the periphery of cylinder 18C. Each peripheral array of straps defines a substantially field-free space or compartment for the associated plunger 17C, or equivalent electrode-moving element. Such straps together with the associated cylinder afford a low resistance path for the heavy circulating currents between the upper wall of the tunnel and the "hot" electrode 16C and no appreciable current flows along the plunger.

Each cylinder 18C and its associated strap members 49C jointly form a columnar inductance element of the applicator and the row of such elements forms an inductance structure, elongated in a direction transverse to the current flow, between electrode 16C and the top wall of the applicator housing 11C.

The applicator 10D, Fig. 6, is similar to that of Figs. 4, 5 in that the vertical cylinders 18D are within the applicator housing 11D. In this modification however, the row of cylinders 18D is within a hollow fin 13D defined by the two conductive webs or sheets 49D disposed on opposite sides of the cylinders and extending lengthwise of the elongated electrode and housing beyond the end cylinders of the row. The opposite ends of each of the sheets 49D are respectively attached, as by bars 56D, 57D, to the upper wall of the housing 11D and to the "hot" electrode 16D. The spaced sheets 49D thus define an elongated fin inductance within which the cylinders 18D and their plungers 17D are disposed in substantial isolation from the high-frequency magnetic and electric fields of the resonant applicator. The cylinders and plungers are shielded from the magnetic field by the spaced sheets 49D and from the electric field by the extension of electrode 16D across their inwardly extending ends. In this modification, neither the cylinders nor their plungers form part of the applicator inductance and they carry no part of the circulating current. In other respects the applicator 10D is similar to those previously discussed and need not be further described.

In the modified press-applicator 10E shown in Fig. 7, the positions of the stationary and movable platens are interchanged, as compared to preceding modifications, so that the vertical cylinders 18E, or equivalent electrode-actuating devices, may be disposed beneath the applicator housing 11E in the press foundations. As in the preceding modifications, the cylinders 18E, or equivalent, extend externally of the housing 11E from one of its side walls. In any of these modifications, the stroke of the side plungers may be small and the applicator adapted for a wide range in width of an edge-bonding load by provision of manually adjustable pressure screws 50E along the opposite side wall.

The stationary electrode 16E is formed by the lower wide and elongated face of a beam 13E attached to the upper wall and forming part of the press frame. The movable electrode 15E of corresponding length and width is supported by or upon two spaced rows of vertical plungers or rams 17E. These rows extend lengthwise of

the electrode 15E. Each of the elongated sides of the movable electrode 15E is connected to the bottom of housing 11E or to the side walls, below the uppermost position of the movable electrode by a series of conductive straps or by a wide flexible web, generically illustrated by flexible members 49E, so to define a substantially field-free space within which the electrode-operating plungers 17E, or equivalent, are disposed, generally as in Figs. 2, 3 and 6.

The capacitance of the resonant applicator 10E is primarily that between the opposed faces of electrodes 15E, 16E. The web or beam 13E is a significant part of the total applicator inductance and substantially all of the remainder consists of the inductance of the straps or webs 49E.

As also in the modifications previously described, the free vertical edges of the inductance structure should be spaced from the ends of applicator housing when such ends are closed, either completely or partially, in order to leave an unobstructed path for the high-frequency magnetic flux encircling such structure. To provide for insertion or removal of work, either or both ends of the applicators 10A—10E may be left open or doors or covers may be provided to minimize interference to sensitive radio-receiving equipment. Closed applicators may be pressure-tight so that dielectric heating may be effected at subatmospheric or superatmospheric pressures. Partial end closures leaving an unobstructed path for insertion or removal of the work from either end of the applicator or for continuous flow of the work through the applicator, as by a conveyor belt, such as indicated at 63D in Fig. 6, may be provided.

The loop 51E may be provided for excitation of the applicator 10E.

In the modification shown in Fig. 8, the fin structure 13F of applicator 10F is hollow to form a completely enclosed shielded compartment or box in which the oscillator tube 25F and associated circuit components may be disposed in isolation from the high-frequency magnetic field encircling the fin and from the high-frequency electric field between the heating electrodes 15F, 16F. In any of the preceding modifications, the space defined by the hollow fin structure may be completely enclosed to insure the space is entirely field-free.

In the particular oscillator circuit 24F shown in Fig. 8, the grid-excitation is provided by loop 71F which extends into the flux space of the applicator on the side of fin structure 13F which is opposite from the anode loop 51F. Thus, there is no appreciable coupling between the loops 51F, 71F except that afforded by the high-frequency magnetic flux encircling the fin inductance 13F. The loops 51F, 71F are so poled or connected that the induced grid voltage is of proper phase for sustained generation of oscillations at a frequency principally determined by the capacity between the heating electrodes 15F, 16F and the inductance of the fin 13F. The condenser 27F and resistor 28F within the hollow fin 13F are for deriving a direct-current grid-biasing voltage from the radio-frequency grid current of the oscillator tube. The condenser 61F within fin 13F is a radio-frequency by-pass or direct-current blocking condenser.

As in Fig. 9, later described, a load tray may be provided for insertion or removal of work 19F, the "hot" electrode 16F being at convenient height for manual loading of plastic preforms or the like; or an insulated conveyor belt moving along or above the elevated "hot" electrode 16F may transport work through the applicator between the electrodes 15F, 16F. In the latter case, the substantial spacing between the edges of the "hot" electrode and the applicator side walls prevents arcing as the work objects pass into or out of the interelectrode space. The applicator 10F may of course be inverted.

The inductance fin structure of tunnel applicators such as herein disclosed need not be symmetrically located in the applicator housing; it may be offset, as in Fig. 9, to

afford space in the housing which may be used for enclosing of the oscillator tube and other circuit components. It is only necessary effectively to isolate such other oscillator elements from the tunnel flux and to provide an adequate path for encirclement of the fin structure by the high-frequency magnetic flux of the resonant applicator.

More specifically, the oscillator tube 25G, associated oscillator-circuit components, and the system components such as blower 68G may be disposed in shielded compartment 64G within the housing 11G of applicator 10G. Other shielded compartments 69G within applicator housing 11G may also be provided for meters, control relays and other power-supply equipment to complete a self-contained mobile unit suited for heating of plastic preforms 19G and for like uses requiring powers of the order of a few kilowatts.

As shown in Fig. 9, such compartments are located to leave a free path for high-frequency magnetic flux to encircle the hollow fin structure 13G which extends from the bottom wall of the applicator housing 11G with the "hot" electrode 16G at its upper end so that the top wall of the housing may serve as the associated "cold" electrode 15G, or so that an adjustable upper electrode (not shown) connected to the top wall may be raised or lowered to accommodate preforms of different height or to vary the effective power-factor of the loaded applicator and so vary the load reflected into the anode circuit of the tube.

The load tray 70G for insertion and removal of the preforms, or other work, may be comprised of a thin sheet of low power-factor material, such as glass or glass fibre-board impregnated with silicone resin, fastened to a metal door or panel 55G which completes closure of the applicator housing when the load tray is inserted. Alternatively, the tray may be made of metal, suitably insulated from the metal door or panel 55G. Tray 70G may simply slide upon and be supported by the "hot" electrode 16G and may be wholly retractable from the applicator housing for loading or removal of work.

A preferred oscillator system for this resonant applicator as well as the others herein described is the oscillator circuit 24G shown in Fig. 9 and more fully described and claimed in my aforesaid applications Serial Nos. 138,628, and 419,633. It automatically maintains proper grid-excitation of the oscillator tube under wide variation of work-load conditions during a run or for widely different work-load conditions of different heating runs.

The loop 51G inductively couples the resonant applicator to the anode circuit of the oscillator tube. The grid of the tube is connected to heating electrode 16G through a capacitor 59G which usually is of high reactance compared to the effective grid-cathode capacity 62G of the tube. In the arrangement shown in Fig. 9, the lead from grid-capacitor 59G extends through an insulator in the top wall of compartment 64G directly to the heating electrode 16G. In such case, the maximum interelectrode voltage, i. e., the voltage between the heating electrodes, is applied to capacitors 59G, 62G in series. Should this be excessively high, the capacitor 59G may be electrically connected to the electrode 16G by a lead extending through the side wall of compartment 64G to a selected point along the fin inductance 13G. In such case, a fraction of the total voltage between the heating electrodes is applied to series capacitors 59G, 62G, the fraction being smaller and smaller as the connection to capacitor 59G is shifted farther and farther along inductor 13G away from electrode 16G.

Condenser 27G and resistor 28G are for deriving a direct-current grid biasing voltage from the rectified grid current. RFC designates a non-resonant choke which provides a high impedance from the grid to the network 27G, 28G. The cathode of the tube, so far as the generated oscillations are concerned, may be grounded directly or through by-pass condensers (not shown).

When, as above pointed out, it is desirable to tap onto the fin structure for grid-excitation, the hollow fin may be

expanded toward the oscillator compartment, whether such compartment is inside or outside the applicator housing, to minimize the grid-lead length while avoiding excessive voltage gradient along the heating electrode. If short grid-lead length were obtained by displacing the fin toward the oscillator compartment, the voltage gradient along the heating electrode might become excessive with large electrodes. Excessive grid-lead length is to be avoided because it causes instability of oscillation operation. Thus hollow fin construction has the additional advantages of facilitating tapping the grid connection onto the fin structure without incurring attendant disadvantages, such as above mentioned, which might otherwise be encountered.

The radio-frequency potential difference between the applicator electrodes may be adjusted to any desired value within a wide range by adjustment of the mutual inductance between the anode loop and the resonant applicator. In the particular arrangement shown in Fig. 9, this is accomplished by the adjustable shorting bar 67G: alternatively such adjustment of the mutual inductance may be effected by rotating the anode loop 51E (Fig. 7) or by any of the various other ways shown in my aforesaid applications Serial Nos. 138,628, and 419,633. As the mutual inductance is varied in a direction to increase the potential of the "hot" electrode, the capacitor 59G is varied in sense to prevent excessive grid-excitation. As the capacity of capacitor 59G is much less than the effective input capacity 62G of the oscillator tube, the radio-frequency (R. F.) potential of the "hot" electrode may be many times higher than the grid-potential, thus permitting the high electrode potential required for dielectric heating without exceeding a safe grid-potential. More particularly, the R. F. grid-potential is always a fraction of the R. F. potential-difference between the heating electrodes and is inversely proportional to the ratio of the total reactance of the series-connected capacitors 59G, 62G to the reactance of the effective input capacity 62G of the oscillator tube (alone or additive to the capacity of an external shunt condenser).

With the mutual inductance or coupling of the applicator and anode circuit adjusted to provide the desired R. F. voltage of electrode 16G, or equivalent, and with capacitor 59G preadjusted or preset for proper grid-excitation, the capacity 62G has an effective value which (as fully explained in my aforesaid applications) inherently varies with the applicator load so that the ratio of the two reactances of the capacitor voltage-divider 59G, 62G varies automatically with load and in proper sense to stabilize the grid-excitation.

The maximum heating-electrode voltage occurs under a condition of "optimum" coupling (between the resonant applicator and the anode circuit) for which the effective resistance R_b, reflected into the anode circuit of the oscillator tube from the applicator, is equal to the effective anode resistance R_p. The corresponding "optimum" mutual inductance (M_o) is given by the equation

$$M_o=\frac{\sqrt{R_pR_s}}{2\pi f} \quad (1)$$

where

f=operating frequency
R_s=effective series-resistance of the applicator

For reasons herein briefly stated but more fully discussed in my aforesaid applications, the mutual inductance between loop 51G, or equivalent, and the resonant applicator is supraoptimum, i. e., higher than "optimum." In such case, the heating electrode voltage does not substantially vary with change in the loaded "Q" of the applicator as would occur, for example, upon change of the characteristics of a dielectric load during its heating or, in a conveyor-fed applicator, upon change in the number of load objects moving between the heating electrodes.

The hollow fin construction facilities supraoptimum coupling, for any given size of anode coupling loop (51E, 51F, 51G), in that by properly dimensioning the fin the flux density through the loop may be increased. Specifically, by increasing the cross-sectional area of the fin structure, greater concentration of flux in the vicinity of the loop may be obtained. The hollow fin construction thus permits supraoptimum coupling to be obtained even when the loop area, for various considerations, should be small.

The operational advantages in dielectric-heating of supraoptimum coupling and the capacity voltage-divider arrangement are more fully discussed in my aforesaid applications.

The applicators of Figs. 8 and 9, as described for heating of plastic preforms, need supply only a few kilowatts (2 to 5 for example) whereas the applicators for heating of wallboard sheets, face-bonding of laminated sheets, etc., such as exemplified by Figs. 1 to 7, supply high power, well over a hundred kilowatts, and employ heating electrodes many feet in length and breadth. In all of them, the R. F. power losses in the resonant applicator are a relatively small percentage of the total R. F. power delivered to the applicator. By way of specific example, a tunnel applicator having an unloaded "Q" of 2750, housing height, length and width of approximately 3, 12 and 8 feet respectively, and a 5-foot by 10-foot electrode of 370 micromicrofarads capacity, and operating at a frequency of 14 megacycles with a peak electrode voltage of 32,000 volts, delivered 148 kilowatts in heating a load having a power-factor of 0.9% with a power loss of only 6 kilowatts in the resonator. A generator using a conventional load circuit having an unloaded "Q" of 200 and delivering the same power (148 kw.) to an identical load would be forced to supply 83 kilowatts of wasted power to the load circuit.

Additional advantages of the hollow fin constructions of these resonant tunnel applicators are that they provide compartments within which the operating mechanism for the heating electrodes, the oscillator tube, or other system components or their connections may be disposed in substantially complete isolation from the intense high-frequency magnetic and electric fields existent in the applicator housing. Moreover, the hollow fin may be of any desired cross-sectional outline, for example, round, rectangular, octagonal or the like, and need not be symmetrically located with respect to the outline of the associated electrode (see, for example, Fig. 9). Thus with economy of fin metal and with flexibility of the fin, when desired, the perimeter of the fin may be suitably large to obtain an inductance of high "Q" and to minimize or control voltage gradients along large electrodes without need for "stubbing" and its attendant complications.

Among the important and singular advantages of resonant applicators such as herein described is that they have made possible, on a commercial scale, the efficient and uniform heating of large sheets or masses of dielectric material of very low power-factor, i. e., of 1% and less, so permitting the application of dielectric heating equipment for such purposes as heating or drying of pulp wallboard, foam rubber, pure gum rubber and the like. With conventional coil circuits or applicators, the percentage of power dissipated as circuit losses is excessively high for power-factors lower than 1%. Furthermore, with conventional coil circuits or applicators, operation at higher frequencies to obtain efficient heating at voltages low enough to prevent arcing, and with elongated electrodes of relatively large area to accommodate large sheets, panels and the like, requires "stubbing" which, aside from difficulties of adjustment, is cumbersome and so reduces the unloaded Q of the heating circuit or applicator that heating of low power-factor loads is impractical.

The use of microwave or very high-frequency generators using waveguides, concentric lines, and conventional resonant cavities requiring complete enclosure and ax-

ial symmetry as applicators is unsatisfactory for applications of dielectric heating involving work of large rectangular area and substantial thickness because of non-uniform heating due to standing waves, localizing of heat at or near the surface of the work, and the low-power, low-voltage limitations of such equipment. In contrast thereto, resonant applicators of the kind herein described may be designed and dimensioned in accordance with principles herein set forth so as to provide, when desired, elongated heating electrodes of large area between which the electric field may be made substantially uniform, without "stubbing," by elongation of the associated inductance structure, and so that operation of the applicators without "stubbing" may be carried on at frequencies which are suitably high or safe, satisfactory heating despite the high electrode capacity required for dielectric loads of great length and area.

In the examples given, and as usually is desirable in resonant applicators such as herein described, the length of the fin inductance in the direction of current flow is very substantially less than a quarter-wavelength at the operating frequency, ordinarily being even less than an eighth-wavelength, and also is less than the maximum dimension of the electrode where elongated electrode structures are employed.

Moreover, when it is desirable to secure substantial uniformity of voltage gradient over the whole of the heating electrode area, this can be accomplished by making at least one face dimension of the electrode structure very much smaller than a wavelength at the operating frequency, and, when an elongated electrode is used, the fin inductance is elongated in the direction of elongation of the electrode so that the length of the fin is very close to, or equal to, the length of the electrode. Still more particularly, in the case of an elongated electrode, its projection, if any, beyond the elongated fin should be substantially less than an eighth-wavelength in the direction of elongation. Also, the amount of projection, if any, of the electrode beyond the fin inductance in the direction at right angles to the direction of elongation of the fin inductance should be substantially less than a quarter-wavelength and usually even less than an eighth-wavelength. For satisfactory commercial operation, it usually is desirable that the half-width of the electrode, taken normal to the direction of elongation of the fin inductance, be substantially less than an eighth-wavelength. By following the principles above set forth, it is possible, with applicators of the kind to which the present invention relates, to employ, when desired, electrodes of large area and relatively great length, i. e., equivalent to as much as one-eighth-wavelength or more at the operating frequency, while obtaining substantial uniformity of voltage gradient over the electrode area without "stubbing."

In batch operation, it usually is desirable to maintain substantial uniformity of voltage gradient throughout the heating electrode area. However, in applicators employing conveyors for continuous feeding of material, it frequently is not so important to maintain uniformity of voltage gradient along the electrode structures in the direction of conveyor travel, thus the electrode structures may be quite long in such direction of conveyor travel, but for reasons set forth above, the dimension of the electrode structure at right angles to the direction of conveyor travel usually should be maintained small relative to a wave-length at the resonant frequency of operation of the applicator. Alternatively, where it is desired to employ an electrode of relatively large dimension in the direction at right angles to the direction of conveyor travel, while maintaining substantial uniformity of voltage gradient in that direction, the fin inductance may be extended in that direction in accordance with principles above set forth.

What is claimed is:

1. A resonant high-frequency electric heating applicator of the reentrant type comprising a housing having electrically conductive walls, electrode structures cooperative to provide an electric field space within said housing for receiving in said field space between said electrode structures material to be heated, a fin-like inductance structure projecting into the interior of the housing and electrically connected at opposite ends respectively to one of said electrode structures and to wall structure of the housing, means including said wall structure completing a resonant circuit which includes said inductance structure and the capacity between said electrode structures, said wall structure providing a low-resistance, low-reactance path as a part of said circuit, and coupling means disposed within the housing in coupling relation with said fin-like inductance structure for supplying high-frequency energy to said resonant circuit for the heating of said material disposed between said electrodes, said housing serving as a shielding enclosure to confine the magnetic field encircling the inductance structure and the electric field produced between the electrode structures, and said inductance structure being hollow and shielded at one end by said one electrode structure to define therein a substantially field-free space effectively isolated from said magnetic and electric fields.

2. A resonant high-frequency heating applicator as in claim 1 in which said hollow inductance structure comprises two members extending in spaced-apart substantially parallel relationship to each other.

3. A resonant high-frequency applicator as in claim 2 in which each of the inductance structure members is continuous.

4. A resonant high-frequency applicator as in claim 2 in which each of the inductance structure members comprises a row of conductive straps.

5. A resonant high-frequency heating applicator as in claim 1 in which auxiliary applicator equipment is disposed within the field-free space defined by said hollow inductance structure.

6. A resonant high-frequency heating applicator as in claim 5, in which said one electrode structure is movable for variation of the spacing between the electrode structures, and in which auxiliary equipment within the hollow inductance structure includes means for effecting such movement of said one electrode.

7. A resonant high-frequency heating applicator as in claim 1, in which said hollow inductance structure is at least in part extensible for variation of the spacing between the electrode structures, and in which actuating mechanism for varying the spacing between the electrode structures is shielded from said fields, at least part of said mechanism being within the field-free space defined by said hollow inductance structure.

8. Apparatus for high-frequency electric heating of dielectric materials comprising a resonant applicator including a housing having electrically conductive walls and electrode structures cooperative to provide an electric field space within said housing for receiving in said field space between said electrode structures material to be heated, an inductance structure within the housing and electrically connected at opposite ends respectively to one of said electrode structures and to wall structure of the housing, means including said wall structure completing a resonant circuit which includes said inductance structure and the capacity between said electrode structures, electrically conductive structure providing a shielding compartment within said housing, and an oscillator system for exciting said applicator and having components disposed within said shielding compartment.

9. Apparatus as defined in claim 8, in which the said inductance structure is hollow and defines said shielding compartment.

10. Apparatus as defined in claim 8, in which a coupling loop extends from said shielding compartment for traverse by the high-frequency magnetic field encircling said inductance structure, said loop being included in an elec-

trode circuit of an oscillator tube within said shielding compartment.

11. A resonant high-frequency heating applicator of the reentrant type comprising spaced heating electrodes for receiving between them material to be heated by the electric field produced between them, a housing having conductive walls of low reactance, a fin-like inductance structure extending inwardly of said applicator from wall structure of said housing to one of said electrodes, said inductance structure being hollow to define therein a field-free space effectively isolated from the high-frequency magnetic field about said inductance structure and said one of said electrodes being disposed across the inwardly extending end of said inductance structure to shield the interior thereof from the high-frequency electric field between said heating electrodes, and coupling means disposed within said housing and in coupling relation to said inductance structure for supplying high-frequency energy to a resonant circuit formed by the inductance of said inductance structure and the capacitance between said spaced heating electrodes for heating said material disposed between them.

12. An applicator for the heating of dielectric work comprising an electrically conductive housing, inductance structure therein comprising a fin inductor projecting into the interior of said housing, spaced electrode structures cooperative to provide electric field space within the housing for receiving therein material to be heated by the electric field between said electrode structures, at least one of said electrode structures being movable to permit variation in the spacing between said electrode structures, said one electrode structure being disposed at the inwardly projecting end of said fin inductor in spaced relation to walls of the housing and being electrically connected with wall structure of the housing through said fin inductor, said wall structure providing a low resistance, low reactance path completing a resonant circuit which includes said inductance structure and said electrode structures and the frequency of which is predominantly determined by the inductance of said inductance structure and the capacitance between said electrode structures, said fin inductor being hollow and said one electrode structure at said inwardly projecting end of said fin inductor shielding the interior thereof to define within said fin inductor a substantially field-free space effectively isolated from said electric field and from the magnetic field about said fin inductor, and mechanism operable to effect movement of said one electrode, at least part of which mechanism is disposed in said field-free space within said fin inductor.

13. An applicator for high-frequency electric heating of dielectric material comprising spaced cooperative electrodes for receiving therebetween the material to be heated, at least one of said electrodes having elongated rectangular configuration and being of large area, a hollow inductance structure electrically connected at one end to said one electrode and having rectangular transverse cross-section shielded by, and of area substantially less than the area of said one electrode, and an electrically conductive housing of rectangular cross-section enclosing said structure and the space between said electrodes and having walls which are in spaced relation to said one electrode, the other end of said inductance structure being electrically connected to wall structure of said housing, said applicator being resonant at a frequency predominantly determined by the inductance of said structure and the capacity between said electrodes, the length of said inductance structure between said wall structure and said one electrode being substantially less than the length of said one electrode, and said inductance structure having such cross-sectional area that the distance therefrom to each edge of said one electrode is substantially less than one-eighth-wavelength at said frequency.

14. A resonant high-frequency applicator as in claim 13, in which the said one electrode is movable for variation of the spacing between said electrodes, and including mechanism for effecting such movement, at least part of which mechanism is disposed within the shielded field-free space inside of said hollow inductance structure.

15. A high-frequency heating applicator comprising walls forming an enclosure, walls forming a shielding compartment within said enclosure, said shielding compartment extending substantially across said enclosure with open space around said compartment between the walls of said compartment and the walls of said enclosure, high-frequency generating equipment enclosed within said compartment, an electrode conductively connected to the upper wall of said compartment and forming a capacitor with the opposing wall of said enclosure, and at least one inductive loop extending into said open space for development between said electrode and said opposing wall of a high-frequency, high-voltage electric field, the walls of said compartment and their conductive electrical connection with said electrode forming the inductance of an oscillatory circuit excited through said loop from said generating equipment, the capacitance of said circuit being determined by the spacing between said electrode and said opposing wall of said enclosure.

16. A resonant applicator comprising a pair of electrodes having substantial breadth and greater length and which are supported in spaced relation one from the other, elongated conductive members spaced from each other in the direction of the width of one of said electrodes and extending in the direction of elongation thereof, each of said members being electrically connected at one elongated end to said one of said electrodes, a conductive-walled housing enclosing said members and the space between said electrodes, and means including wall structure of said housing electrically connecting the other elongated ends of said conductive members to the other electrode and forming a confined path for the high-frequency magnetic field about said members.

17. A resonant applicator for high-frequency electric heating of dielectric materials comprising an electrically conductive housing, inductance structure disposed in said housing and including at least one inductive element of hollow cross-section and relatively large cross-sectional area, spaced electrode structures cooperative to provide electric field space within the housing, one of which electrode structures is disposed at one end of said inductive element in spaced relation to wall structure of the housing and electrically connected with said wall structure through said inductive element, means including said wall structure completing a resonant circuit which includes said inductance structure and said electrode structures, said housing serving as a shielding enclosure to confine the electric field produced between said electrode structures and the magnetic field encircling said inductance structure, and a conveyor for transporting material through said electric field space, said one electrode structure having substantially greater area than the cross-sectional area of said inductive element and extending beyond said element on both sides, in the direction at right angles to the direction of conveyor travel, a distance which is substantially less than one-eighth-wavelength at the operating frequency of the resonant applicator.

18. A resonant high-frequency heating device comprising a tunnel applicator having conductive walls whose resistance and reactance are negligible, a high-frequency heating electrode within said applicator in spaced relation to all walls thereof, a second electrode providing with said heating electrode substantially all the capacitance of said applicator, means for moving said heating electrode toward and from one of said walls for varying the potential gradient through a load being heated, said means including actuating metallic members conductively connected to said heating electrode and to the opposite

one of said walls, a metallic inductor surrounding said actuating members to isolate said actuating members from high-frequency fields within said applicator and to provide substantially all the inductance of said resonant device, and means for electrically connecting the opposite ends of said inductor respectively to said heating electrode and to said opposite wall of the applicator, said connecting means at least at one end of the inductor comprising flexible conductors.

19. A resonant high-frequency heating device comprising a tunnel applicator having conductive walls whose resistance and reactance are negligible, high-frequency heating electrode structure within said applicator in spaced relation to all walls thereof, a hollow metallic inductor structure attached at one end to said electrode structure and at the opposite end to a wall of said applicator, said inductor providing substantially all the inductance of said tunnel applicator, and means for moving said heating electrode structure toward and from a wall of said applicator for varying the potential gradient through a load to be treated, said means comprising metallic members conductively attached to one of said structures within the field-free boundary of said inductor structure and conductively engaging and passing through an opposite wall of said applicator.

20. A resonant high-frequency heating applicator comprising an enclosure having conductive walls whose resistance and reactance are negligible, heating electrode structure within said enclosure in spaced relation to walls thereof, inductance structure comprising a hollow inductive element electrically connected at one end to said electrode structure and electrically connected at an opposite end to said enclosure, the interior of said element comprising a field-free space, said inductance structure providing substantially all the inductance of said applicator, means for moving said electrode structure toward or away from a load to be heated, said means comprising at least one metallic member conductively attached to one

of said structures within said field-free space of said inductive element and passing through one of said walls within an area encompassed by said inductive element.

21. An applicator for the heating of dielectric work comprising an electrically conductive housing, inductance structure therein comprising a fin inductor projecting into the interior of said housing, and spaced electrode structures cooperative to provide electric field space within the housing for receiving therebetween material to be heated by the electric field between said electrode structures, one of said electrode structures being disposed at the inwardly projecting end of said fin inductor in spaced relation to walls of the housing and electrically connected with wall structure of the housing through said fin inductor, said wall structure providing a low resistance, low reactance path completing a resonant circuit which includes said inductance structure and said electrode structures and the frequency of which is predominantly determined by the inductance of said inductance structure and the capacitance between said electrode structures, said fin inductor being hollow and said one electrode structure at said inwardly projecting end of said fin inductor shielding the interior thereof to define therein a substantially field-free space effectively isolated from said electric field and from the magnetic field about said fin inductor.

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